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Corresponding Author: Dr. Andres Seco, Dr.

Corresponding Author's Institution: Universidad Publica de Navarra

First Author: Sandra Espuelas

Order of Authors: Sandra Espuelas; Angel Maria Echeverria; Sara Marcelino; Eduardo Prieto; Andres Seco, Dr.

Abstract: Portland cement is a widely used binder in construction and building applications because of its good properties. Despite its convenience as construction material, the social demands and policies trends are requesting a lower impact and more sustainable cement manufacturing industry. The most effective ways to reach this goal are the substitution of clinker by different wastes or by-products in the cement composition or the development of more sustainable binders like the alkali activated binders. This work analyzes from a technical and environmental point of view the substitution of a clinker based CEM I common cement for the construction mortars manufacturing. Four common cements with different ground granulated blastfurnace slags (GGBS) or fly ashes (FA) contents as well as fifteen alkali activated binders (AAB) combinations were considered. Fresh consistency, density, unconfined compressive strength (UCS) tests and life cycle analysis were carried out to state the ability of these different hydraulic and alkaline activated binders for the CEM I substitution. The results obtained demonstrated the technical and environmental convenience of these binders for the construction mortars manufacturing.

Suggested Reviewers: John Kinuthia Dr.
professor, Faculty of Computing, Engineering and Science, University of South Wales
john.kinuthia@southwales.ac.uk

Abid Abu Tair Dr.
professor, Faculty of Engineering & IT People, The British University in Dubai
abid.abu-tair@buid.ac.ae

Jamal Khatib Dr.
professor, School of Engineering and the Built Environment, University of Wolverhampton
j.m.khatib@wlv.ac.uk

Benat Garcia Dr.
professor, Mining and Metallurgical Engineering and Materials,
Universidad del Plais Vasco
benat.garcia@ehu.es

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TECHNICAL AND ENVIRONMENTAL CHARACTERIZATION OF HYDRAULIC AND ALKALINE BINDERS

S. Espuelas[(1)], A.M. Echeverria[(2)], S. Marcelino[(3)], E. Prieto[(4)], A. Seco[(5)(*)]

[(1)] Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: sandra.espuelas@unavarra.es . Phone: +34948169682; Fax: +34948169148).

[(2)] Zabala Innovation Consulting S.A. 31192 Mutilva (E-mail: amecheverria@zabala.es. Phone: 34948198000; Fax: 34948198000)

[(3)] Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: sara.marcelino@unavarra.es. Phone: +34948169224; Fax: +34948169148)

[(4)] Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: epc@unavarra.es . Phone: +34948169177; Fax: +34948169148

[(5)] Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: andres.seco@unavarra.es. Phone: +34948169682; Fax: +34948169148)

[(*)]Corresponding author

TECHNICAL AND ENVIRONMENTAL CHARACTERIZATION OF HYDRAULIC AND ALKALINE BINDERS

ABSTRACT

Portland cement is a widely used binder in construction and building applications because of its good properties. Despite its convenience as construction material, the social demands and policies trends are requesting a lower impact and more sustainable cement manufacturing industry. The most effective ways to reach this goal are the substitution of clinker by different wastes or by-products in the cement composition or the development of more sustainable binders like the alkali activated binders. This work analyzes from a technical and environmental point of view the substitution of a clinker based CEM I common cement for the construction mortars manufacturing. Four common cements with different ground granulated blastfurnace slags (GGBS) or fly ashes (FA) contents as well as fifteen alkali activated binders (AAB) combinations were considered. Fresh consistency, density, unconfined compressive strength (UCS) tests and life cycle analysis were carried out to state the ability of these different hydraulic and alkaline activated binders for the CEM I substitution. The results obtained demonstrated the technical and environmental convenience of these binders for the construction mortars manufacturing.

KEYWORDS

Mortar; alkali-activated binder; hydraulic cement; wastes valorization; ground granulated blast furnace slag, fly ash; Life Cycle Analysis

TECHNICAL AND ENVIRONMENTAL CHARACTERIZATION OF HYDRAULIC AND ALKALINE BINDERS

1. INTRODUCTION

Portland Cement (PC) is the finely ground, non-metallic, inorganic powder, obtained from natural rocks calcination who, when is mixed with water, forms a paste that sets and hardens. PC is the most widely used hydraulic binder for the construction and building industries around the world since its invention in the XIX Century. It became the essential product that nowadays is because of its good mechanical properties, durability and relatively low economic cost ((Juenger et al, 2010; Babaee and Castel, 2016). Thus, concrete, mortars and plasters manufacturing, soils stabilization or pavement bounded layers construction, among other applications consume huge amounts of this binder. Only in European Union the cement industry, in 2011 produced 195.5 Mt, what represented 5.6% of total world production (European Commission, 2018a).

Despite the convenience of this material, PC sector has to face up an important challenge as is its lack of sustainability: Manufacturing of PC is an energy intensive production process that results in an energy consumption of approximately between 3500 and 5000 MJ/PC tonne and 0.9 to 1 CO_2 tonnes/PC tonne (Pacheco et al., 2010; European Commissiion, 2013; Maddalenaa et al., 2018). This supposes approximately 2-3 % of the use of primary world energy and 5 to 10 % of the total of manmade CO_2 emissions (Damtoft et al., 2008; Bellmann and Stark, 2009; Habert et al., 2011; Maddalena et al., 2018). Nowadays cement manufacturing is moving towards lower carbon and more energy efficient production ways, in accordance with the actual social demands, economy and climate and energy policies trends (European Commission, 2018b).

An effective way to improve the sustainability of the PC is its partial substitution by additives with lower environmental impact. For example, the European Standard EN 197-1, considers the substitution of clinker by different products up to 80% for the common cements manufacturing.

These are materials rich in silicon and aluminum reactive oxides, which in themselves possesses little or no cementitious value but who, finely grounded, react with the calcium oxide present in the PC to form cementitious compounds. Some of these additives are industry wastes or byproducts, like Ground Granulated Blastfurnace Slags (GGBS) of Fly Ashes (FA), which use for the cement manufacturing contributes to their valorization ((Prusinski et al., 2006; O'Brien et al., 2009; Aïtcin, 2008; Seco et al., 2012). As these additives usually do not require to be calcined, their use is not only an effective way to save natural resources but also contributes to diminish CO_2 emissions (Prusinski et al., 2006; Maddalena et al., 2018). In addition, many of the cements containing these products can show improved properties compared to the PC, like increased mechanical strength, enhanced resistance to aggressive environments or improved durability (Andrade y Bujak, 2012; Le Saoûtet al., 2013; Lorca et al., 2014).

Other way to improve the sustainability in these applications where cement is widely used is its substitution with lower environmental impact binders. Thus, Alkali-Activated Binders (AAB) are receiving increasing attention as possible alternatives to PC, because of their potential, based on their usually high mechanical properties, good durability and lower manufacturing environmental impact (Shi et al., 2011; Zhang et al, 2016; Provis, 2017). These binders are composed of a precursor material, rich in silicon and aluminum reactive oxides, and an alkaline activator solution. In the high pH conditions, created by the activator, cementitious silicon and aluminum polymers, named geo-polymers, are created (Shi et al., 2011; Provis, 2017). The AAB characteristics depend on the precursor and activator properties, existing many works that demonstrated their good mechanical strength, low permeability and high durability (Khan et al, 2016; Zhang et al.,2016; Mobili et al., 2016;

Provis, 2017). As well as in the case of the hydraulic cements, different by products and wastes can be used as AAB precursors, contributing to highlighting the better environmental characteristics of these binders compared to PC (McLellan et al., 2011).

In spite of the general consensus about the environmental convenience of the PC substitution, the quantification of the increase of sustainability that alternate products suppose, remains as an open discussion. For this, mortars based on different hydraulic and AABs and a sand were manufactured and tested. From the technical point of view, fresh mortar setting time and consistence as well as final Unconfined Compressive Strength (UCS) tests, were considered. The environmental characterization of the samples was carried out by means of the Life Cycle Analysis (LCA) methodology with and without standardizing the results based on the binders mechanical properties.

2. MATERIALS

Five different cements, manufactured in accordance with the European Standard EN 197-1, were used for the laboratory investigation. This Standard considers five groups (I-V) of common cements, based on their composition. The cement designation contains its type, followed by its mechanical strength at 28 days. Thus, CEM I 52.5 is a common cement mainly made of clinker, who obtained 52.5 MPa in the Unconfined Compressive Strength (UCS) test. Besides CEM I 52.5, four other cements, containing different substitutions were considered in this work. Table 1 shows the composition of the hydraulic cements considered as well as their UCS.

TABLE 1

GGBS is a by-product obtained during the manufacture of pig iron in the blast furnace, who is formed by the combination of iron ore with limestone flux. Quickly cooled, little or no crystallization occurs and it shows a glassy state. This process results in the formation of sand size fragments, usually with some friable clinker-like material. Finely grounded, this material shows an important reactivity based on its richness in calcium, aluminum and silicon oxides.

GGBS used in this study for the AABs manufacturing was supplied by *Hanson Heidelberg Cement Group* (UK). Table 2 shows the chemical composition of the available GGBS sample, expressed as oxides, obtained by X Ray Fluorescence (XRF).

TABLE 2

FA is a fine waste powder resulting of the combustion of coal in electric power generating stations. In this study, a FA classified as class F in according with the ASTM C 615 Standard, was used for the AABs manufacturing. The available FA sample was supplied by *Cementos Tudela Veguín S.A.* Table 2 shows its chemical composition as main oxides, obtained by XRF analysis.

The alkaline activators consisted of 6, 8 and 10 molar NaOH solutions, mixed with sodium silicate (Na_2O•3.3SiO_3) at a rate 70-30% respectively, based on (Fernandez-Jimenez et al, 2006), among others. NaOH solutions were prepared by the dissolution of pure NaOH flakes into distillated water. To avoid the effect of the heat released during the solution preparation, over the AABs activation kinetic, the solutions were prepared and kept in closed containers at 20 C for 24 hours, before their use.

A commercial 1-2 mm granulometry calcareous sand, obtained from limestone rock crushing, was used as aggregates for the mortar samples manufacturing.

3. METHODS

3.1. MORTAR SAMPLES MANUFACTURING

Table 3 shows the mortar combinations considered for the laboratory investigation carried out. A total of five hydraulic cement and thirteen AAB based mortars were prepared.

TABLE 3

Both types of mortar samples, hydraulic and alkali-activated ones, were manufactured with a constant 1:2 binder to sand ratio. To guarantee similar workability conditions in all the samples, in each case it was added the required amount of water to get a drain consistency value of 175±5 mm, in accordance with the European Standard EN 1015-3. For the hydraulic mortars manufacturing, cement and sand were previously mixed in a laboratory mortar mixer for 10 minutes. After this dry mixing, it was carefully added the required amount of water to reach the consistency conditions as previously defined. The wet mixing was maintained for 10 minutes to guarantee the homogenization of the mortar sample. For the alkali activated mortar samples manufacturing, the precursor was directly mixed with the activator and the water. The precursor to activator rate was maintained in a constant 7:3 ratio based on Shi et al. (2006) and Yang (2011) among others, meanwhile the water quantity varied in each case depending on the consistency test. Samples were mixed for 10 minutes in a laboratory mortar mixer till their complete homogenization. Hydraulic and alkaline activated fresh samples were poured in 50x50x50 mm steel molds and vibrated for 5 minutes in a vibrating table to take out any possible air bubble as well as for the correct filling of the molds. Finally mortars were cured in wet chamber at 20 C and 100% Relative humidity until the test ages of 7, 14, 21 and 28 days.

3.2. SAMPLES CHARACTERIZATION

Setting time and fresh consistency tests, in accordance with the European Standards EN 480-2 and EN 1015-3 respectively, were considered for the fresh mortars characterization. Cured mortars mechanical strength was characterized by means of the UCS, carried out in accordance with the procedure defined in the European Standard EN 1015-11.

In order to quantify the environmental impact of each mix, a Life Cycle Analysis (LCA) was carried out in accordance with the ISO 14044 (2006) Standard. The functional unit chosen was one tonne of mortar and the limits of the analysis were "from the cradle to the gate (LCAI)", following the approach of Marcelino-Sadaba et al. (2017). GGBS and FA were considered by-products based on the EU legislation (European Commission, 2008). So that, proportional emission were assigned to both materials, based on Chen et al. (2010) and Gala et al. (2015). In accordance with Heijungs (1992), the environmental impacts evaluated included Climate Change, acidification, eutrophication and dust generation categories expressed respectively as CO_2, PO_4, SO_2 and dust equivalent emissions. Emissions inventory data were obtained from (Dunlap, 2003; Kellenger and Althaus, 2003; Habert et al., 2005; Althaus, 2007; Louise and Franks, 2013; The European Cement Association, 2017 and SimaPro databases 4.0).

Table 4 shows the impact due to the manufacturing of one tonne of each mortar constituent material of the considered environmental categories.

TABLE 4

4. RESULTS AND DISCUSSION

4.1. SETTING TIME AND FRESH CONSISTENCY

Figure 1 shows the starting and final setting times of the mortars samples.

FIGURE 1

Mortars based on hydraulic cements required the long starting setting times because of their hydration process kinetic. The quicker and the slowest starting setting times corresponded to the CEM III/A 42.5 with 198 minutes and to the CEM V/A 32.5, with 242 minutes respectively. If the setting period is considered (difference between the starting and finishing of the setting time), the mortar with the longest setting period is CEM IV/B 32.5, with 92 minutes. The shorter setting period corresponds to CEM III/B 32.5 with 40 minutes. Despite the setting times differences, no relationship with the cement components or resistance were observed.

Alkali activated mortars showed much shorter starting setting times, as expected based on the known rapid kinetic of the alkaline binders. Thus, the quicker alkali activated mortars starting setting time corresponded to the GGBS 10M and GGBS 75:25 FA 10M combinations, with 12 minutes. The slowest starting setting time was achieved by FA 6M, with 52 minutes. In the case of the alkali activated binders, inverse relationships between GGBS content and activator molarity to starting setting time were observed. The setting period varied from 39 minutes, corresponding to GGBS 10M up to 86 minutes in the case of GGBS 50:50 FA 6M combination.

Table 5 shows the water added/binder ratio needed to get the consistency of 175±5 mm as well as the cured density of these mortars.

TABLE 5

Hydraulic cements required a water to cement ratio between 0.394 and 0.442 to get the needed workability. Alkaline mortars required lower quantities of added water because of the activator, who contains 70% of a NaOH dissolution. For all the activator molarities, combinations with 100% FA as precursor, required the lowest amounts of added water who increased as the GGBS content did. In addition, an inverse relationship between the activator molarity and the water added was observed. Thus, at the 6M molarity, the water added ratio varied from 0.150 for the FA precursor up to 0.227 for the GGBS. At 8M, the ratios decreased to 0.106 and 0.159 respectively. For the 10M molarity the lowest ratios were obtained with values from 0.084 to 0.157 for the same precursors.

Hydraulic mortars densities were very similar for all the samples, reaching values between 2.07 and 2.09 g/cm^3. In the case of the alkaline mortars, densities were related to the precursor kind: FA and GGBS combinations varied between 2.08-2.11 g/cm^3 and 2.14-2.15 g/cm^3 respectively. No relationships between activator molarity and mortar densities were observed in this parameter.

4.2. UNCONFINED COMPRESSIVE STRENGTH

Figure 2 shows the UCS test results obtained for each combinations, tested at 7, 14, 21 and 28 days.

FIGURE 2

CEM I 52.5 N cement based mortar was considered as reference for the other hydraulic as well for the alkali activated combination because of its pure clinker composition. This cement showed an UCS value at 7 days of 27.0 MPa with a rapid increase of strength up to 44.4 MPa at 14 days. After that, its resistance increased slowly, reaching a maximum value of 47.4

MPa, at the age of 28 days. The other cement combinations showed lower mechanical properties, based on their own cement characteristic resistances. Thus, the following best result among the hydraulic mortars was obtained by the cement CEM III/A 42.5 N combination. At 7 days, this sample obtained 30.2 MPa, increasing slightly its strength till the 28 days age, when it got 37.2 MPa. CEM V/A 32.5 N showed slightly lower resistance than CEM III/A 42.5 N combination, with a similar strength increase pattern. It showed an initial UCS value of 26.5 MPa at 7 days that steadily increased up to 36.5 MPa at 28 days. Finally, CEM IV/B 32.5 N and CEM III/B 32.5 N showed the lower UCS values for all the curing ages: They obtained 16.7 and 15.6 MPa at 7 days who increased up to 30.5 and 25.4 MPa respectively at 28 days.

Alkali activated mortars showed strength values and development patterns based mainly on the precursor nature. Thus, GGBS combinations obtained the highest UCS values at all the testing ages, for all the activator molarities. The best results were obtained by the GGBS 6M combination: at 7 days it reached 55.3 MPa who increased up to 66.8 MPa at the age of 28 days. With 8M and 10M activators GGBS absolute strengths values decreased but they did not show a clear pattern of resistance lose related to the activator molarity increase. For example, considering the 28 days tests, GGBS 8M decreased to 61.0 MPa and GGBS 10M increased again, reaching 62.1 MPa. FA demonstrated its low ability for the geopolimerization: for all the activator molarities their absolute UCS values were very low, showing a weak increase pattern along the curing time. As well as in the case of the GGBS, FA reached its best final value of 6.7 MPa at the age of 28 days, with the 6M activator. For 8M and 10M molarities no significant strength differences were obtained at the same testing ages.

The mixes of GGBS and FA showed intermediate strength values in between both precursors, depending on the mix ratio. As expected, based on the GGBS and FA own results, richer in

GGBS combinations showed higher UCS values for all the molarities and testing ages except for the GGBS 75:25 FA 6M combination at 7 and 14 days when it is overcome by the GGBS 50:50 FA 6M one. All the mixed precursor combinations reached their highest resistance values with the 6M activator, obtaining 52.7, 54.2 and 56.8 MPa as GGBS ratio increased from 25 till 75%.

4.3. LIFE CYCLE ANALYSIS

Table 6 shows the absolute, and relative to CEM I 52.5 percentage values impacts, due to the manufacturing of each mortar combinations.

TABLE 6

In general hydraulic mortars show higher environmental impacts than the alkali activated ones for the climate change, acidification and eutrophization categories and lower for the dust emissions. This is due to the fact that this impact category depends mainly on the activator compounds. In the case of the hydraulic mortars, as the only change among combinations is the cement, their environmental impacts differences depends on the cement kind. Thus, the CEM I 52.5 combination shows the highest impacts for all the environmental categories. The other cement combinations show different values due to the rates of clinker substitution by GGBS and FA in their compositions. Among the alkaline mortars the impacts depend mainly on the relative proportions between the precursor compounds and, in a lower extent, on the activator molarities: As the differences of NaOH contents between the different activator molarities change slightly, the activator weight on the total binder impact is lower than the precursor's one. Like GGBS shows higher manufacturing impacts than FA except for the eutrophication category, as FA content increases, environmental impact decreases for the climate change, acidification and dust categories. By other side, impact increases as activator molarity does because of the higher NaOH content and because the high emissions of the NaOH for all the categories. In the table 6 the higher and the lower impact combinations for each environmental categories are highlighted. CEM I 52.5 is the worse combination for the climate change, acidification and eutrophication and GGBS 10M is the worse for the dust. On the other hand, the most environmental friendly combinations depend on the impact category considered.

Table 7 shows the mortar combinations impacts normalized by UCS strength unit.

TABLE 7

From this point of view, hydraulic mortars normalized impacts, related to CEM I 52.5, increase, moreover CEM III/A 42.5 and CEM III/B 32.5 because of their lower USC values. CEM I 52.5 continues being the hydraulic combination with the highest emissions for all the environmental categories. In the case of the alkaline mortars, normalized impacts related to CEM I 52.5 show a different behavior than the non-normalized ones. Mostly of the combinations containing GGBS show relative lower normalized impacts related to CEM I 52.5 than their non-normalized values. This is due to the fact that in them except GGBS 25:75 FA 8M and 10 M, and GGBS 50:50 FA 10M. On the other hand, 100% FA combinations reached the worse normalized emissions results for all the impact categories at all the molarities because of their low mechanical properties.

5. CONCLUSIONS

This experimental investigation allowed to state the technical and environmental differences between hydraulic and alkaline binders for the mortars manufacturing. Based on the fresh properties, cured mechanical strength and environmental analysis carried out, the following specific conclusions were obtained:

1. Hydraulic mortars reached longer starting setting times than the alkaline ones. In the case of the hydraulic mortars, starting setting time were not related to the cement compositions or the UCS values. By other hand, Alkali activated mortars showed shorter starting setting times with inverse relationships with GGBS content and activators molarities.
2. Despite the starting setting times differences observed, the setting periods were similar and they did not show any pattern neither for the hydraulic nor for the alkaline mortars.
3. Hydraulic combinations required the highest amounts of water added to reach the workability consistence because of the lack of other water sources in the mixes. Alkaline mortars showed an inverse relationship between the needs of water added and the FA content and activator molarity.
4. Densities reached were very close in hydraulic mortars. In general alkali combinations showed slightly higher values, directly related to the GGBS content.
5. Hydraulic mortars showed regular UCS increase patterns along the curing time except for the CEM I 52.5 combination which main increase of resistance occurred before the 14 days age. UCS final values depended on the cement resistance properties, with some variability among the three 32.5 MPa cements considered. On the other hand alkali mortars showed UCS values directly related to the precursors GGBS content and inversely related to the FA content as well as to the activators molarities. Mechanical properties showed strong increases at all the testing ages, for all the molarities even for the lower GGBS content. This demonstrated the convenience of this precursor for the high strength alkali activated binders manufacturing.

6. From an environmental point of view the results obtained for the different mortars were different when, non-normalized or normalized data, were considered. Non-normalized results show each combination constituents impacts. Thus, CEM I 52.5 combination reaches the worse impacts in three of the four environmental categories, except for the dust because of the highest impacts in this category of the activators compounds. Based on this point of view there is not a clearly more environmental combination because the best combination changes, depending on the impact categories. When normalized results are considered, FA 10M becomes the worse combination for all the impact categories, because of the low mechanical properties demonstrated when the FA was the only compound of the precursor. GGBS 6M reached the best values for the acidification and eutrophication and close to the best values for the climate change and dust impact categories, demonstrating to be the best overall combination from the environmental point of view.

As final conclusions it can be stated that common cements containing GGBS and FA as clinker substitution as well as alkali activated binder can be effective ways to decrease the environmental impact related to the manufacturing of conventional construction mortars, maintaining the technical properties of this material.

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Dear Sir,

We are pleased to send you the manuscript **TECHNICAL AND ENVIRONMENTAL CHARACTERIZATION OF HYDRAULIC AND ALKALINE BINDERS** for the purpose of being published in the *Journal of Cleaner Production*.

This work focuses in the technical and environmental properties of different hydraulic and alkaline binders based on different waste materials, compared to the Portland Cement manufactured from clinker. Common cements containing GGBS and FA as clinker substitution as well as alkali activated binder demonstrated to be an effective way to decrease the environmental impact related to the manufacturing of conventional construction materials, maintaining their technical properties.

Yours sincerely,

The authors.

TECHNICAL AND ENVIRONMENTAL CHARACTERIZATION OF HYDRAULIC AND ALKALINE BINDERS

HIGHLIGHTS

1. Hydraulic mortars reached longer starting setting times than the alkaline ones.
2. Setting periods were similar for the hydraulic and for the alkaline mortars.
3. Hydraulic binders required more water added than the alkaline ones.
4. GGBS allows the high strength alkali activated binders manufacturing
5. GGBS and FA decrease the impact related to the binders manufacturing

Figure1

FIGURE 1. Mortars setting time. a) Hydraulic cements, b) Alkaline binders 6M, c) Alkaline binders 8M, d) Alkaline binders 10M.

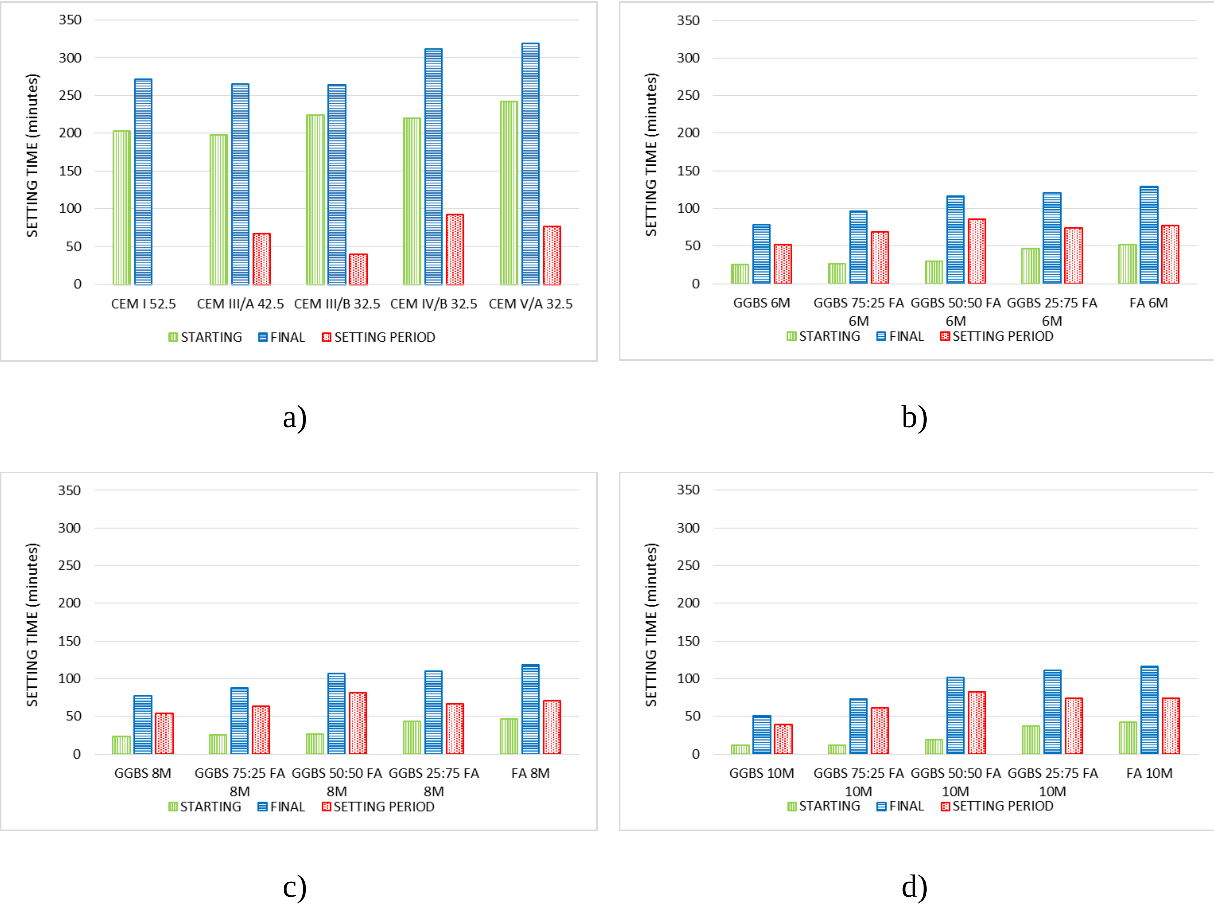
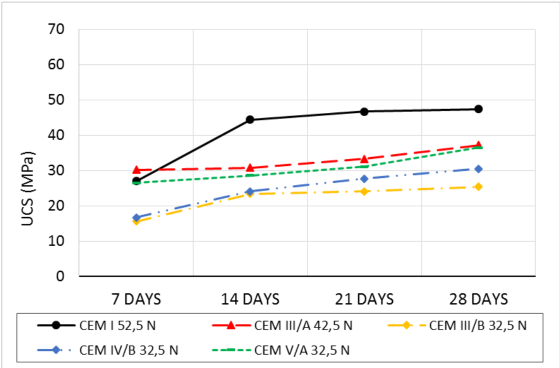
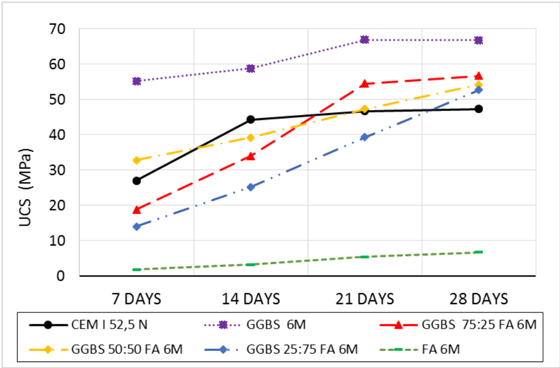


Figure2

FIGURE 2. UCS test results. a) Hydraulic cements, b) Alkali activated 6M binders, c) Alkali activated 8M binders and d) Alkali activated 10M binders.



a)



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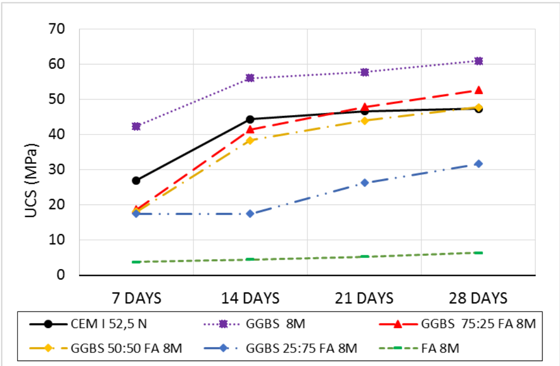

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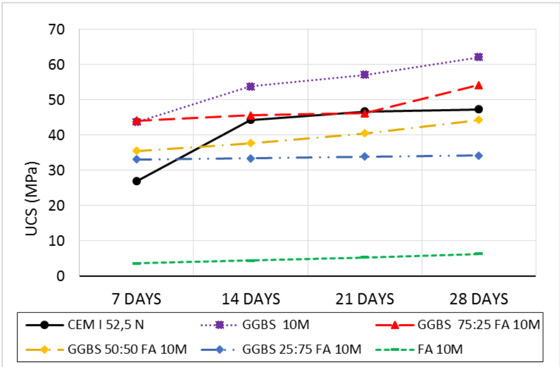

d)

TABLE 1. Components (wt.%) of the considered common cements.

CEMENT	UCS (MPa)	COMPONENTS (%)				
		Clinker	Limestone	FA	GGBS	Gypsum
CEM I 52.5	52.5	95	2	-	-	3
CEM III/A 42.5	42.5	54	-	-	41	5
CEM III/B 32.5	32.5	25	-	-	70	5
CEM IV/B 32.5	32.5	49	-	49	-	2
CEM V/A 32.5	32.5	40	-	27	28	5

Table2

Table 2. Characterization of the AAB precursors samples. Chemical composition is expressed as main oxides in weight percentage.

CHEMICAL RICHNESS		
Oxides	GGBS	FA
CaO	41.9	3.9
Al_2O_3	11.6	18.4
SiO_2	35.5	49.1
MgO	8.0	1.5
Others	3.0	27.1
SUPPLIER	Hanson Heidelberg Cement Group	Cementos Tudela Veguín S.A.
Country of origin	UK	Spain

Table3

TABLE 3. Hydraulic and alkaline mixes tested in the laboratory investigation.

		HYDRAULIC BINDERS	ALKALINE BINDERS		
			PRECURSOR (wt. %)		ACTIVATOR
COMBINATION	SAMPLE CODE	CEMENT	GGBS	FA	NaOH (M)
1	CEM I 52.5	CEM I 52.5	-	-	-
2	CEM III/A 42.5	CEM III/A 42.5	-	-	-
3	CEM III/B 32.5	CEM III/B 32.5	-	-	-
4	CEM IV/B 32.5	CEM IV/B 32.5	-	-	-
5	CEM V/A 32.5	CEM V/A 32.5	-	-	-
6	GGBS 6M	-	100	-	6
7	GGBS 75:25 FA 6M	-	75	25	6
8	GGBS 50:50 FA 6M	-	50	50	6
9	GGBS 25:75 FA 6M	-	25	75	6
10	FA 6M	-	-	100	6
11	GGBS 8M	-	100	-	8
12	GGBS 75:25 FA 8M	-	75	25	8
13	GGBS 50:50 FA 8M	-	50	50	8
14	GGBS 25:75 FA 8M	-	25	75	8
15	FA 8M	-	-	100	8
16	GGBS 10M	-	100	-	10
17	GGBS 75:25 FA 10M	-	75	25	10
18	GGBS 50:50 FA 10M	-	50	50	10
19	GGBS 25:75 FA 10M	-	25	75	10
20	FA 10M	-	-	100	10

Table4

Table 4. Emissions due to the manufacturing of one tonne of each mortar constituents.

MATERIAL	Climate change GWP100 (kg CO_2 eq.)	Acidification potential – average Eur (kg SO_2 eq.)	Eutrophication – generic (kg PO_4eq.)	Dust (kg particles eq.)
Sand	6.48E+00	2.01E-02	1.98E-03	1.21E-02
GGBS	1.26E+02	6.12E-02	1.96E-05	7.59E-02
Fly ash	9.51E+00	5.90E-02	2.55E-03	4.90E-02
NaOH	1.23E+03	6.90E+00	3.90E-01	5.34E+00
Sodium silicate	6.89E+02	1.63E+00	2.28E-01	7.09E+00
Clinker	8.57E+02	2.43E+00	3.35E-01	8.52E-01

Table5

TABLE 5. Water amount added to the mortars and density. a) Hydraulic cements, b) Alkaline binders 6M, c) Alkaline binders 8M, d) Alkaline binders 10M.

COMBINATION	SAMPLE CODE	Added water/binder	Density (g/cm^3)
1	CEM I 52.5	0.442	2.09
2	CEM III/A 42.5	0.445	2.09
3	CEM III/B 32.5	0.426	2.09
4	CEM IV/B 32.5	0.394	2.07
5	CEM V/A 32.5	0.395	2.09
6	GGBS 6M	0.227	2.14
7	GGBS 75:25 FA 6M	0.180	2.11
8	GGBS 50:50 FA 6M	0.162	2.10
9	GGBS 25:75 FA 6M	0.153	2.09
10	FA 6M	0.150	2.04
11	GGBS 8M	0.159	2.14
12	GGBS 75:25 FA 8M	0.154	2.08
13	GGBS 50:50 FA 8M	0.124	2.06
14	GGBS 25:75 FA 8M	0.105	2.04
15	FA 8M	0.106	2.06
16	GGBS 10M	0.157	2.15
17	GGBS 75:25 FA 10M	0.144	2.11
18	GGBS 50:50 FA 10M	0.115	2.09
19	GGBS 25:75 FA 10M	0.108	2.07
20	FA 10M	0.084	2.04

Table6

Table 6. Environmental impact due to the manufacturing of one tonne of each mortar combinations.

COMBINATION	SAMPLE CODE	ENVIRONMENTAL IMPACT				RELATIVE TO CEM I 52.5 MORTAR (%)			
		Climate change GWP100 (kg CO_2 eq.)	Acidification potential – average Eur (kg SO_2 eq.)	Eutrophication – generic (kg PO_4eq.)	Dust (kg particles eq.)	Climate change GWP100 (kg CO_2 eq.)	Acidification potential – average Eur (kg SO_2 eq.)	Eutrophication – generic (kg PO_4eq.)	Dust (kg particles eq.)
1	CEM I 52.5	2.19E+02	6.23E-01	8.52E-02	2.22E-01	100.0	100.0	100.0	100.0
2	CEM III/A 42.5	1.44E+02	3.80E-01	5.09E-02	1.43E-01	65.8	61.0	59.7	64.2
3	CEM III/B 32.5	9.12E+01	2.08E-01	2.66E-02	8.63E-02	41.6	33.4	31.2	38.8
4	CEM IV/B 32.5	1.13E+02	3.19E-01	4.34E-02	1.20E-01	51.7	51.2	50.9	53.9
5	CEM V/A 32.5	1.11E+02	2.97E-01	3.93E-02	1.14E-01	50.5	47.7	46.2	51.1
6	GGBS 6M	5.69E+01	1.44E-01	1.11E-02	2.39E-01	26.0	23.1	13.0	107.6
7	GGBS 75:25 FA 6M	5.17E+01	1.44E-01	1.12E-02	2.38E-01	23.6	23.1	13.1	107.1
8	GGBS 50:50 FA 6M	4.65E+01	1.44E-01	1.13E-02	2.37E-01	21.2	23.1	13.2	106.5
9	GGBS 25:75 FA 6M	4.13E+01	1.43E-01	1.14E-02	2.35E-01	18.8	23.0	13.4	106.0
10	FA 6M	3.61E+01	1.43E-01	1.15E-02	2.34E-01	16.5	23.0	13.5	105.4
11	GGBS 8M	6.18E+01	1.71E-01	1.26E-02	2.60E-01	28.2	27.5	14.8	117.2
12	GGBS 75:25 FA 8M	5.66E+01	1.71E-01	1.27E-02	2.59E-01	25.8	27.5	14.9	116.7
13	GGBS 50:50 FA 8M	5.14E+01	1.71E-01	1.28E-02	2.58E-01	23.5	27.5	15.1	116.1
14	GGBS 25:75 FA 8M	4.62E+01	1.71E-01	1.30E-02	2.57E-01	21.1	27.5	15.2	115.6
15	FA 8M	4.10E+01	1.71E-01	1.31E-02	2.55E-01	18.7	27.5	15.3	115.0
16	GGBS 10M	6.67E+01	1.99E-01	1.42E-02	2.82E-01	30.5	31.9	16.6	126.8
17	GGBS 75:25 FA 10M	6.15E+01	1.99E-01	1.43E-02	2.80E-01	28.1	31.9	16.8	126.3
18	GGBS 50:50 FA 10M	5.63E+01	1.99E-01	1.44E-02	2.79E-01	25.7	31.9	16.9	125.7
19	GGBS 25:75 FA 10M	5.11E+01	1.99E-01	1.45E-02	2.78E-01	23.3	31.9	17.0	125.2
20	FA 10M	4.59E+01	1.98E-01	1.46E-02	2.77E-01	21.0	31.9	17.2	124.6

Table7

Table 7. Environmental impact due to the manufacturing of one tonne of each mortar combinations normalized by UCS strength unit.

COMBINATION	SAMPLE CODE	ENVIRONMENTAL IMPACT				RELATIVE TO CEM I 52.5 MORTAR (%)			
		Climate change GWP100 (kg CO_2 eq.)	Acidification potential – average Eur (kg SO_2 eq.)	Eutrophication – generic (kg PO_4eq.)	Dust (kg particles eq.)	Climate change GWP100 (kg CO_2 eq.)	Acidification potential – average Eur (kg SO_2 eq.)	Eutrophication – generic (kg PO_4eq.)	Dust (kg particles eq.)
1	CEM I 52.5	4,62E+00	1,31E-02	1,80E-03	4,69E-03	100.0	100.0	100.0	100.0
2	CEM III/A 42.5	3,87E+00	1,02E-02	1,37E-03	3,83E-03	83.7	77.6	76.0	81.7
3	CEM III/B 32.5	3,60E+00	8,20E-03	1,05E-03	3,40E-03	77.8	62.4	58.3	72.6
4	CEM IV/B 32.5	3,71E+00	1,04E-02	1,42E-03	3,92E-03	80.1	79.5	78.9	83.6
5	CEM V/A 32.5	3,03E+00	8,13E-03	1,08E-03	3,11E-03	65.6	61.8	59.9	66.4
6	GGBS 6M	8,51E-01	2,15E-03	1,66E-04	3,58E-03	18.4	16.4	9.2	76.3
7	GGBS 75:25 FA 6M	9,11E-01	2,53E-03	1,97E-04	4,19E-03	19.7	19.3	10.9	89.3
8	GGBS 50:50 FA 6M	8,58E-01	2,65E-03	2,08E-04	4,36E-03	18.5	20.2	11.6	93.1
9	GGBS 25:75 FA 6M	7,83E-01	2,72E-03	2,16E-04	4,46E-03	16.9	20.7	12.0	95.2
10	FA 6M	5,39E+00	2,14E-02	1,72E-03	3,49E-02	116.5	162.8	95.5	745.6
11	GGBS 8M	1,01E+00	2,81E-03	2,07E-04	4,27E-03	21.9	21.4	11.5	91.1
12	GGBS 75:25 FA 8M	1,08E+00	3,25E-03	2,42E-04	4,92E-03	23.2	24.7	13.4	105.0
13	GGBS 50:50 FA 8M	1,08E+00	3,58E-03	2,69E-04	5,39E-03	23.3	27.2	14.9	115.1
14	GGBS 25:75 FA 8M	1,46E+00	5,39E-03	4,09E-04	8,09E-03	31.5	41.0	22.7	172.6
15	FA 8M	6,46E+00	2,69E-02	2,06E-03	4,02E-02	139.7	204.8	114.4	858.4
16	GGBS 10M	1,07E+00	3,20E-03	2,28E-04	4,53E-03	23.2	24.4	12.7	96.7
17	GGBS 75:25 FA 10M	1,14E+00	3,67E-03	2,64E-04	5,17E-03	24.6	27.9	14.7	110.4
18	GGBS 50:50 FA 10M	1,27E+00	4,48E-03	3,25E-04	6,29E-03	27.5	34.1	18.0	134.3
19	GGBS 25:75 FA 10M	1,50E+00	5,81E-03	4,25E-04	8,13E-03	32.3	44.2	23.6	173.5
20	FA 10M	7,23E+00	3,13E-02	2,30E-03	4,36E-02	156.4	237.9	128.1	930.0